Published in final edited form as:

Magn Reson Med. 2016 June ; 75(6): 2388–2393. doi:10.1002/mrm.25843.

Improved spoiling efficiency in dynamic RF-spoiled imaging by ghost phase modulation and temporal filtering

Jon-Fredrik Nielsen and Douglas C. Noll

Department of Biomedical Engineering, University of Michigan, Ann Arbor, MI, USA

Abstract

Purpose—RF-spoiled steady-state sequences offer rapid data acquisition with T1- or T2*-weighting. The spoiler gradients in these sequences must be large enough to suppress ghosting artifacts, and are chosen empirically. However, certain factors such as the need to minimize gradient first moments or acoustic noise can limit the spoiler size and hence the ability to suppress ghosts. We present an acquisition and pre-processing strategy for improved spoiling efficiency in conventional and echo-shifted (ES) dynamic RF-spoiled 3D imaging.

Theory and Methods—By requiring each time-frame in a dynamic imaging sequence to contain a particular (restricted) number of total RF shots, the ghost signal can be made to alternate in sign every other frame. The ghost is then suppressed by Fourier transforming along the temporal dimension, and removing the Nyquist frequency in pre-processing (similar to UNFOLD). The method works for both Cartesian and non-Cartesian imaging.

Results—We demonstrate improved ghost suppression with the proposed approach, for both conventional and echo-shifted spoiled gradient echo imaging (SPGR) in stationary phantoms and *in vivo*. Cartesian ES-SPGR produces two ghosts shifted in opposite directions, both of which are suppressed with our method.

Conclusion—For a given spoiler gradient area, the proposed approach substantially suppresses the ghost signal in both conventional and echo-shifted dynamic RF-spoiled imaging.

INTRODUCTION

RF-spoiled steady-state sequences offer rapid data acquisition with T1- or T2*-weighting, and are used for, e.g., dynamic contrast-enhanced imaging, quantitative T1 mapping, and 3D functional MRI (1–3). The unbalanced gradient lobes (spoiler gradients) in these sequences must be large enough to suppress ghosting artifacts, and are generally chosen empirically since the required spoiler size and direction for “good” artifact suppression is subjective and may be sequence- and application-dependent (4–8). For example, in Cartesian spoiled gradient-echo imaging (SPGR/FLASH/T1-FFE) it has been suggested that the same unbalanced gradient should be applied along both readout and slice encoding directions, with a gradient moment producing at least one spoiling cycle (2π) per voxel along the direction with highest spatial resolution (4). However, even if this condition is met, partial

* Correspondence to: Jon-Fredrik Nielsen, PhD, 1067 B.I.R.B., 2360 Bonisteel Ave, Ann Arbor, MI 48109 - 2108, Phone: 734-647-7728, jfnielse@umich.edu.

volume effects can cause incomplete dephasing, causing ghosting at edges and tissue interfaces. Furthermore, in non-Cartesian imaging such as 3D stack-of-spirals, it may be difficult to visually determine the level of artifact suppression. For these reasons, it is often difficult to know whether good spoiling has been achieved.

Although spoiling efficiency can always be improved in principle by increasing the spoiler gradient area, certain practical or application-dependent factors can limit the choice of spoiler gradients, either in size or direction. In echo-shifted RF-spoiled imaging (ES-SPGR) (2, 3), increasing the spoiler gradients increases the gradient first moment, which makes the sequence more susceptible to flow- and motion-induced phase instabilities from one TR to the next. Furthermore, for a given spoiler gradient area A, ES-SPGR with one-TR echo shift requires a total gradient of 3A, which can increase the sequence TR, acoustic noise, and gradient duty cycle significantly. Regarding gradient direction, in stack-of-spirals 3D imaging with multiple spiral leaves per z “platter” it can be convenient (from a sequence implementation perspective) to apply the spoiler gradient on the through-plane axis only, since each spiral leaf should be balanced so as not to rotate the unbalanced gradient along with each leaf. This prevents the spoiler gradient from being “shared” among all three spatial directions, which may limit the peak gradient and hence make the gradient duration longer than strictly needed.

In applications where multiple RF-spoiled images are to be averaged, e.g., to increase signal-to-noise ratio (SNR), Leupold et al. (9) showed that spoiling efficiency can be improved by exploiting the periodicity of the signal with respect to the RF shot “counter” n . In particular, by separating each acquisition by a certain number of RF shots the ghost phase can be varied across images in a controlled manner, such that the ghosts cancel when averaged. For example, for $N = 2$, the ghost phase in the two images can be made to differ by 180° . With this scheme, the spoiler gradient moment can be reduced by a factor N equal to the number of averages. In dynamic RF-spoiled imaging, however, a different approach is needed.

Here we present an acquisition and pre-processing strategy for improved spoiling efficiency in dynamic RF-spoiled imaging, by dynamically modulating the phase of the ghosts at the Nyquist frequency and removing that frequency component in pre-processing. Our approach is based on (9), but rather than using averaging as an intrinsic part of the spoiling process, the periodicity of the RF-spoiled signal is exploited to make the ghost phase alternate between 0° and 180° in subsequent frames (relative to the main object). This allows for ghost suppression by temporal filtering. We show that for a given spoiler gradient area, the proposed approach substantially suppresses the ghost signal in both SPGR and ES-SPGR. With this approach we demonstrate 3D RF-spoiled dynamic imaging in phantoms and *in vivo* with minimal ghosting using only one cycle (2π) of gradient spoiling applied in the through-plane direction.

THEORY

In RF-spoiled imaging the RF phase increment from the $(n-1)^{\text{th}}$ RF shot to the next is set to $\psi \times n$, where ψ is a constant (e.g., 117° , 50° , or 150°) (1). The steady-state magnetization

m_n^+ immediately following the n^{th} RF pulse is a superposition of different configurations F_m^+ (10),

$$m_n^+ \propto \sum_m e^{-imn\psi} e^{im\theta} F_m^+ = \dots + e^{in\psi} e^{-i\theta} F_{-1}^+ + F_0^+ + e^{-in\psi} e^{i\theta} F_1^+ + e^{-i2n\psi} e^{i2\theta} F_2^+ + \dots \quad [1]$$

where θ denotes the locally accumulated spin phase per TR (including the spoiler gradient). A single configuration, e.g., F_0^+ (FID) or F_1^+ (one-TR ES-SPGR), is nominally selected by playing out a suitably unbalanced gradient prior to data acquisition such that undesired configurations are fully dephased (due to the $e^{im\theta}$ term). However, for insufficient spoiler gradients (incomplete dephasing across a voxel) residual unwanted configurations F_m^+ can contribute to the acquired signal. For example, in Cartesian imaging, residual signal from the nearest neighboring configurations, e.g., F_{-1}^+ and F_1^+ for FID imaging, or F_0^+ and F_2^+ for one-TR ES-SPGR, give rise to ghosts that are shifted along the phase-encode direction by an amount proportional to ψ . For higher-order configurations the effective spoiler gradient moment increases proportionally to the distance in configuration space (e.g., the $m=2$ configuration effectively experiences twice the gradient spoiler moment compared to the $m=1$ configuration), and hence higher-order configurations typically contribute negligibly to the acquired signal. Therefore, here we are mainly concerned with the “primary” ghosts from the nearest neighboring configurations in FID and ES-SPGR imaging.

When imaging the FID ($m=0$) configuration, the F_{-1}^+ (ECHO) signal is usually negligible (10), and hence only one ghost is typically observed. In one-TR ES-SPGR, however, both F_0^+ and F_2^+ are visible, appearing as ghosts on either side of the main object.

Our ghost suppression method is based on the observations that (i) the phase of the primary ghosts in 3D RF-spoiled Cartesian images is a function of the initial value of the RF shot counter n at the beginning of a frame, and (ii) the RF-spoiled steady-state signal is periodic in n . These properties can be understood from Eq. [1]: First, we see that the phase of the signal from neighboring configurations relative to the main signal is given by

$$\pm\psi \times n = \pm \left[\psi \times n_o + \psi \times n' \right] \quad [2]$$

where n_o is the value of n at the beginning of a frame, and $n' \equiv n - n_o = 0, 1, 2, \dots, (n - 1)$, counts the RF shots for one frame. n is the total number of RF shots used to acquire one frame. The second term in Eq. [2] gives rise to a spatially shifted ghost (assuming Cartesian imaging), while the constant term determines the phase of the ghost relative to the main object. This means that in a dynamic imaging sequence, the ghost phase will generally be different from one frame to the next. Second, from Eq. [1] we also see that the signal is periodic in n . In particular, the RF-spoiled steady-state signal repeats every P shots satisfying

$$P \times \psi = 360 \times K \quad [3]$$

with integer numbers K and P having no common divisor (9). For example, for $\psi = 117^\circ$ we have $P = 40$ and $K = 13$.

From this we can conclude that if the number of RF shots n separating two subsequent frames satisfies

$$\Delta n = \frac{P}{2} \times c, \quad c = \text{odd integer}, \quad [4]$$

the ghosts in two subsequent frames appear in the same location but are exactly 180° out of phase. This means that by simply separating neighboring frames in a dynamic imaging sequence by a n satisfying Eq. [4], the ghosts can be made to oscillate in sign at the temporal Nyquist frequency. Here we are assuming that identical k-space samples are acquired for all frames, and that equivalent samples in subsequent time-frames are separated by a n satisfying Eq. [4] (in other words, the k-space sampling order from frame to frame may be different as long as Eq. [4] is satisfied for each pair of subsequent k-space samples). The ghosts can then be suppressed in a manner similar to UNFOLD (11), i.e., by performing a Fourier transform (FFT) operation along the temporal dimension on the raw k-space data, and removing the Nyquist frequency in pre-processing. In the case of Cartesian imaging, the temporal filtering can be performed in either image space or k-space.

In non-Cartesian imaging such as stack-of-spirals, Eq. [2] still holds, however the “ghost” signal source does not produce an easily recognizable copy of the main object. Nevertheless, the same acquisition and temporal filtering strategy can be applied regardless of readout trajectory, provided that Eq. [4] holds for subsequent k-space samples as stated above.

METHODS

All imaging studies were performed on a GE 3T scanner equipped with a quadrature (birdcage) transmit/receive head coil and an 8-channel receive head array. We acquired 3D RF-spoiled acquisitions with $\psi = 117^\circ$ and one cycle (2π) per voxel of spoiling along the through-slab (z) direction. We evaluated three types of RF-spoiled sequences: (1) Cartesian SPGR, (2) Cartesian ES-SPGR, and (3) stack-of-spirals ES-SPGR. Both ES-SPGR sequences used a one-TR echo delay.

Phantom imaging

To demonstrate the proposed ghost suppression approach, we acquired dynamic SPGR and ES-SPGR images of a stationary water-filled structural phantom with the birdcage coil [flip angle 10° ; $1 \times 1 \times 3 \text{ mm}^3$ voxels; matrix size $240 \times 210 \times 14$; 20 temporal frames; TE/TR = 4.9/10.5 ms (SPGR) and 15.4/10.4 ms (ES-SPGR)]. The resulting total acquisition time TR_{vol} per frame was approximately 31 sec. The matrix was chosen to satisfy Eq. [4] with $c = 147$ ($P = 40$). The z (partition) encoding was done in the outer scan loop, and both y and x encoding was done in a linear fashion as is typically done. The ES-SPGR pulse sequence is

shown in detail in Fig. 3(a). Apart from the echo-shifting gradients (green), the SPGR sequence was nearly identical. For comparison, we also acquired an SPGR data set with matrix size $240 \times 200 \times 14$, which does not satisfy Eq. [4] and hence should not be compatible with the proposed temporal filtering approach. After 3D inverse Fourier transforming into image space, the complex image time-series for one slice was Fourier transformed (FFT'd) along the temporal dimension, the Nyquist component was set to zero, and the spectrum was inverse FFT'd to produce the final “pre-processed” image time-series.

Human volunteer imaging

To demonstrate the use of the proposed approach with non-Cartesian readouts, and to evaluate the ghost suppression *in vivo*, we acquired dynamic 3D Cartesian and stack-of-spirals ES-SPGR images in a volunteer using the 8-channel receive array. The Cartesian ES-SPGR acquisition was identical to that used in the phantom experiment. We reconstructed the 3D Cartesian data using inverse 3D FFT. The resulting image time-series was temporally filtered in the manner described above for the phantom experiments, except that both the Nyquist temporal frequency component and the two nearby frequencies (on either side) were also removed.

Stack-of-spirals acquisition parameters were: flip angle 10° ; $3 \times 3 \times 3$ mm³ voxels; matrix size $80 \times 80 \times 38$; 30 temporal frames; 3 spiral-in leaves per kz “platter”; TE/TR=32/18 ms. These acquisition parameters are suitable for, e.g., functional MRI studies. To ensure that Eq. [4] is satisfied ($c = 7$; $P = 40$), 26 “dummy” RF shots were played out at the end of each frame. The total acquisition time TR_{vol} per frame, including the dummy shots, was 2.5 s. The z encoding was done in the outer scan loop, in a linear fashion. In other words, all three spiral leaves were acquired before moving to the next z-encode. Prior to image reconstruction, the Nyquist and two neighboring (on either side) temporal frequency components were removed from the acquired k-space data. We subsequently reconstructed a 3D image time-series using inverse FFT and nonuniform FFT (12) in the through- and in-plane dimensions, respectively, implemented with the IRT Matlab toolbox (<http://www.eecs.umich.edu/~fessler>).

RESULTS

Phantom SPGR imaging results are shown in Figs. 1 and 2. Figure 1 shows that with the proposed acquisition scheme (Eq. [4]), the ghost phase in a dynamic SPGR (FID) sequence oscillates between 0 and 180° relative to the main object. Figure 2(a) shows two subsequent frames both before and after the proposed temporal filtering, and shows that the primary ghost in each frame has been effectively suppressed. For comparison, Fig. 2(b) shows results for a matrix size that violates Eq. [4], and in this case we observe that the temporal filtering step does not remove the ghosts.

Figure 3 shows dynamic ES-SPGR imaging results in the stationary phantom. In ES-SPGR, both neighboring ghosts are prominent, and both ghosts are effectively suppressed with our approach.

Finally, Fig. 4 shows *in vivo* dynamic ES-SPGR imaging results, for both Cartesian and stack-of-spirals imaging. As in Fig. 3, in the Cartesian acquisition in Fig. 4 we observe two

ghosts shifted in the positive and negative phase-encoding directions, respectively. In both Cartesian and stack-of-spirals ES-SPGR imaging, the proposed correction method leads to a significant reduction in ghost artifacts, as evidenced visually by the reduced image intensity outside the object after temporal filtering.

DISCUSSION

We have shown that our acquisition and pre-processing scheme improves ghost suppression in both conventional and echo-shifted RF-spoiled steady-state imaging. With the proposed method, we obtained good spoiling with only one cycle (2π) of nominal dephasing over the largest voxel dimension (3 mm through-plane). This seems sufficient for stack-of-spirals ES-SPGR imaging (Fig. 4), and it may be possible to use even smaller spoilers in some applications as there is no strict requirement to apply an integer number of spoiling cycles (4). However, larger spoilers may be needed in some applications. For example, some ghosting remains in the *in vivo* Cartesian ES-SPGR images after the proposed correction (Fig. 4), perhaps due to partial-volume. It is also possible that B0 inhomogeneity in these regions is sufficiently severe to significantly counteract the through-slab spoiler gradient, causing incomplete dephasing. In this case it may therefore be necessary to use a larger gradient spoiler. Hence, even with our approach there is likely still a need for some level of *ad hoc* spoiler selection.

The temporal filters used in this study were the simplest possible, consisting of simply setting the Nyquist and sometimes neighboring frequency components to zero. In our proof-of-principle phantom studies we obtained good results by setting only the Nyquist component to zero, whereas *in vivo* we found that ghost correction improved by also removing neighboring components due to the broader frequency spectrum. This comes at the cost of loss of temporal frequency content, which must be weighed against the improvement in ghost suppression. We anticipate that a more principled approach to filter selection that takes into account the expected object bandwidth and desired level of ghost suppression will produce a more robust and generally applicable pre-processing routine than the one used here.

To satisfy Eq. [4] it is necessary to either restrict the acquisition matrix or play out additional “dummy” RF shots as we did in the stack-of-spirals *in vivo* experiment (Fig. 4). With the latter approach, the choice of ψ impacts the worst-case time penalty per time-frame: For example, the worst-case penalty is $39 \times \text{TR}$ when $\psi = 117^\circ$, since the signal repeats every 40 RF shots. For, e.g., $\psi = 150^\circ$, the signal repeats every 12 RF shots and hence the worst-case time penalty is only $11 \times \text{TR}$.

The underlying imaging principle proposed here can also be used to remove ghosts in averaged RF-spoiled imaging, e.g., by acquiring an equal number of images with 0° and 180° relative ghost phase and simply averaging the acquired k-space or complex Cartesian images.

CONCLUSIONS

We have demonstrated a simple method for more effective ghost suppression in dynamic SPGR and ES-SPGR imaging, based on frame-to-frame modulation of the ghost phase. Our approach is easy to implement and may allow for robust dynamic RF-spoiled imaging even with relatively small spoiler gradients, e.g., one cycle of dephasing per voxel applied along a single gradient axis. This approach may be particularly useful in dynamic echo-shifted RF-spoiled imaging (e.g., 3D fMRI), where large spoiler gradients can increase the flow-encoding moments, acoustic noise, and peripheral nerve stimulation significantly.

ACKNOWLEDGMENTS

An earlier version of this manuscript relied on resetting the TR counter n at the beginning of each frame, which produces the same desired ghost phase modulation as described here but introduces transient oscillations. We thank an anonymous reviewer for pointing out that such a reset is not necessary provided that n is chosen according to Eq. [4], and for explaining our method in the context of Eq. [1].

Grant Sponsors:

National Institutes of Health (5R01NS058576)

National Institutes of Health (5R21EB012674)

REFERENCES

1. Zur Y, Wood ML, Neuringer LJ. Spoiling of transverse magnetization in steady-state sequences. *Magn Reson Med*. 1991; 21:251–263. [PubMed: 1745124]
2. Liu G, Sobering G, Duyn J, Moonen CT. A functional MRI technique combining principles of echo-shifting with a train of observations (PRESTO). *Magn Reson Med*. 1993; 30:764–768. [PubMed: 8139461]
3. van Gelderen P, Duyn JH, Ramsey NF, Liu G, Moonen CT. The PRESTO technique for fMRI. *Neuroimage*. 2012; 62:676–681. [PubMed: 22245350]
4. Leupold J, Hennig J, Scheffler K. Moment and direction of the spoiler gradient for effective artifact suppression in RF-spoiled gradient echo imaging. *Magn Reson Med*. 2008; 60:119–127. [PubMed: 18581420]
5. Denolin V, Azizieh C, Metens T. New insights into the mechanisms of signal formation in RF-spoiled gradient echo sequences. *Magn Reson Med*. 2005; 54:937–954. [PubMed: 16155898]
6. Zou, Y.; Middione, MJ.; Srinivasan, S.; Ennis, DB. Analysis of Gradient Spoiling in Phase Contrast MRI. In Proc., ISMRM; 21st Annual Meeting; Salt Lake City. 2013. p. p4436
7. Middione MJ, Wu HH, Ennis DB. Convex gradient optimization for increased spatiotemporal resolution and improved accuracy in phase contrast MRI. *Magn Reson Med*. 2014; 72:1552–1564. [PubMed: 24347040]
8. Yarnykh VL. Optimal radiofrequency and gradient spoiling for improved accuracy of T1 and B1 measurements using fast steady-state techniques. *Magn Reson Med*. 2010; 63:1610–1626. [PubMed: 20512865]
9. Leupold J, Hennig J. Increasing spoiling efficiency in RF-spoiled gradient echo sequences by averaging of RF phase-cycle-adapted k-spaces. *Magn Reson Med*. 2011; 66:1123–1128. [PubMed: 21394780]
10. Ganter C. Steady state of echo-shifted sequences with radiofrequency phase cycling. *Magn Reson Med*. 2006; 56:923–926. [PubMed: 16892200]
11. Madore B, Glover GH, Pelc NJ. Unaliasing by fourier-encoding the overlaps using the temporal dimension (UNFOLD), applied to cardiac imaging and fMRI. *Magn Reson Med*. 1999; 42:813–828. [PubMed: 10542340]

12. Fessler JA, Sutton BP. Nonuniform fast Fourier transforms using min-max interpolation. *IEEE Trans Sig Proc.* 2003; 51:560–74.

Author Manuscript

Author Manuscript

Author Manuscript

Author Manuscript

Figure 1.

Dynamic 3D SPGR images of a stationary phantom ($\psi = 117^\circ$). The matrix size is chosen to satisfy Eq. [4] ($n = 210 \times 14 = 20 \times 147$). Six consecutive frames are shown, for a central slice. (a) Magnitude images, showing a significant ghost artifact in each frame. (b) Phase images, after subtracting the image phase of frame 1 from each frame. The ghost phase oscillates between 0° and 180° as desired, while the main object phase remains constant.

Figure 2.

Proof-of-principle demonstration of ghost removal in dynamic SPGR imaging by ghost phase modulation and temporal filtering. Two consecutive time-frames from two dynamic 3D SPGR scans are shown ($\psi = 11^\circ$), both before (top) and after (bottom) removal of the Nyquist temporal frequency component. Only one of the 14 acquired slices is shown. Results are shown for matrix sizes (a) $240 \times 210 \times 14$, which satisfies Eq. [4], and (b) $240 \times 200 \times 14$, which violates Eq. [4]. Only when Eq. [4] is satisfied (Fig. (a)) are the ghosts removed, as expected.

Figure 3.

Ghost correction in dynamic Cartesian 3D ES-SPGR imaging, proof-of-principle demonstration in a stationary phantom. (a) Pulse sequence timing diagram, with unbalanced gradients in green. (b) Phase image time-series, after subtracting the image phase of frame 1 from each frame. The acquisition matrix was the same as in Fig. 2(a), and satisfies Eq. [4]. In ES-SPGR, both neighboring ghosts (corresponding to $m = 0$ and $m = 2$ in Eq. [1]) are prominent, and the phase of both ghosts oscillates at Nyquist frequency as desired. (c) Time-series images before and after the proposed correction.

Figure 4.

Ghost correction in dynamic Cartesian and stack-of-spirals 3D ES-SPGR imaging, in vivo results. In each panel, two consecutive frames are shown, for the middle slice in the acquired 3D volume. ‘5x’ refers to a five-fold reduction in the display window, to allow better visualization of ghost artifacts outside the brain. (a) Cartesian (spin-warp) imaging results, using the sequence in Fig. 3(a) [$1 \times 1 \times 3 \text{ mm}^3$ voxel; $240 \times 210 \times 14$ matrix; FOV 24 cm; $TE/TR/TR_{\text{vol}} = 15.4\text{ms}/10.4\text{ms}/31\text{s}$]. (b) Stack-of-spirals imaging results, using a similar sequence as in (a) except with balanced 3-leaf spiral readouts [$3 \times 3 \times 3 \text{ mm}^3$ voxel; $80 \times 80 \times 38$ matrix; FOV 24 cm; 3 spiral-in leafs; $TE/TR/TR_{\text{vol}} = 32\text{ms}/18\text{ms}/2.5\text{s}$].